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PERIOD CLUSTERING OF THE ANOMALOUS X-RAY PULSARS AND MAGNETIC FIELD DECAY IN MAGNETARS

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ABSTRACT

We confront theoretical models for the rotational, magnetic, and thermal evolution of an ultra-magnetized neutron star, or magnetar, with available data on the Anomalous X-ray Pulsars (AXPs). We argue that, if the AXPs are interpreted as magnetars, their clustering of spin periods between 6 and 12 seconds, observed at present in this class of objects, their period derivatives, their thermal X-ray luminosities, and the association of two of them with young supernova remnants, can only be understood globally if the magnetic field in magnetars decays significantly on a time scale of the order of 10^4 years.

Subject headings: stars: neutron — stars: magnetic fields — pulsars: general — X-rays: stars

1. INTRODUCTION

The bright compact X-ray sources 1E 2259+586, 4U 0142+61, 1E 1048.1-5937, 1E 1841-045 and 1RXS J170849-40091 comprise a small class of distinct objects (Mereghetti & Stella 1995), known as the "Anomalous X-ray Pulsars" (AXPs), whose spin periods P are clustered around 8 s, and are found to be spinning down rapidly with period derivatives $\dot{P}$ in excess of $5 \cdot 10^{-13}$ s s^{-1}. Their X-ray luminosities L_X in the range of $10^{34} - 10^{36}$ erg s^{-1} and their soft spectra make them peculiar among the brighter and harder X-ray pulsators found in the Galaxy. The absence of a stellar companion and/or of a circumstellar disk at the sensitivity limits of current optical/IR searches (Mereghetti, Israel & Stella 1998; Coe & Pightling 1998) lead to the hypothesis that AXPs are isolated neutron stars endowed with an unusually large magnetic field $B \gg 10^{13}$G (Vasisht & Gotthelf 1997) that is decaying in order to power the X-ray emission (Thompson & Duncan 1996). This hypothesis is strengthened by the association of both 1E 2259+586 and 1E 1841-045 with young ($\lesssim 10^4$ yr) supernova remnants (SNRs) suggesting that AXPs are isolated young neutron stars with hot cores. There are several AXP candidates which await future determination of their $\dot{P}$ for confirmation. Of these, the 7 s pulsar AX J1845-0258 (Torii et al. 1998; Gotthelf & Vasisht 1998) has recently been found to be centered on a SNR (Gaensler et al. 1999), while the enigmatic source RX J0720.4-3125 (Haberl et al. 1997) has a period of 8.39 s but a lower X-ray luminosity for an AXP.

Duncan & Thompson (1992) had proposed that neutron stars with huge interior magnetic fields $\sim 10^{15} - 10^{16}$G can exist (Woltjer 1964), and that in these magnetars the magnetic energy rather than the rotational energy is the main source powering their emission. If it is true that a large magnetic field decays dramatically through non linear processes such as ambipolar diffusion and/or a Hall cascade (Goldreich & Reisenegger 1992), magnetic energy is continuously dissipated into heat making the neutron star incandescent and brighter than a coeval neutron star with a non decaying field. AXPs may be a manifestation of this phenomenon as observed on the time scales of $\sim 10^3 - 10^4$ yr (Thompson & Duncan 1996; Heyl & Kulkarni 1998, thereafter H&K).

In the $P-\dot{P}$ diagram this handful of "candidate" magnetars occupy a narrow vertical strip along the P axis in the range between 6 and 12 seconds. The lower limit is usually considered to be a natural consequence of the initial rapid spin-down due to the postulated ultra-strong magnetic field. But then why has no AXP with longer period been yet detected ? In this letter we want to address this issue by exploring various scenarios concerning the thermal and magnetic evolution of ultra-magnetized neutron stars and consider their consequences on the rotational history of the star.

2. THE CONSTANT MAGNETIC FIELD SCENARIO

If we assume that the magnetic field of the neutron star is constant, then magneto-dipolar radiation will cause rapid spin-down to periods of

$$P \approx 8 \ \ (B/10^{15}\mathrm{G})(t/10^3\mathrm{yr})^{1/2} \ \mathrm{s}. \tag{1}$$

Given the observed periods of AXPs, this implies that they must become suddenly undetectable after a few thousand years. A rapid fading of the thermal X-ray luminosity is predicted by cooling models of ultra-strongly magnetized neutron stars due to the early dominance of the photon cooling over the previous neutrino cooling. The age at which the abrupt transition to photon cooling occurs depends sensitively on the chemical composition of the envelope, and on the specific heat of the star's core which is controlled mostly by neutron superfluidity (Page 1998). Apparently, the most optimistic models indicate that this age is around, but definitely above, 10^4 yr. This scenario thus naturally leads to an upper observable period of AXPs of several tens of seconds, considering field strengths above 10^{14} G.

3. THE DECAYING MAGNETIC FIELD SCENARIOS

A decaying magnetic field has two important effects on our concerns. First, it will lead to an asymptotic satura-

tion period and, second, it will maintain the thermal X-ray luminosity high enough for detection during a longer time.

The three main avenues of field decay, as described by Goldreich and Reisenegger (1992), are ambipolar diffusion, in the irrotational and solenoidal modes, and the Hall cascade. Ambipolar diffusion only acts in the neutron star core while the Hall cascade can act in both the core and the crust. Results of the magneto-thermal evolution driven by ambipolar diffusion have been presented by H&K. We will call hereon avenue A for the irrotational mode, and avenue B for the solenoidal mode of field decay. Geppert et al. (1999) recently studied the case of a magnetic field confined to the crust with its decay induced by the Hall cascade (our avenue C), which resulted in a much faster decay than in the case of a field permeating the core.

3.1. *Field and period evolution*

The results of all these numerical calculations can be well fitted by simple decay laws of the form

$$\frac{dB}{dt} = -a\; B^{1+\alpha} \tag{2}$$

for the surface magnetic field, which implies

$$B(t) = \frac{B_0}{[1 + a\alpha B_0^\alpha\; t]^{1/\alpha}} \tag{3}$$

where B_0 is the initial field strength that we let vary between 10^{13} and 10^{16} G. Figure 1 shows the evolution of the magnetic field for these models which is relevant for AXPs. (The values of the parameters are given in the Figure 1 caption, in units of 10^6 yr for t and 10^{13} G for B.) The decay law (eq.[2] or [3]) holds while the current field is strong (i.e., $B(t) > 10^{13}$ G), in all the three avenues. Assuming again magneto-dipolar braking, $P\dot{P} = bB^2$ with $b \approx 10^{-39}$ cgs (i.e., $b \approx 3$ when B is measured in 10^{13} G, P in seconds and $\dot{P}$ in seconds per 10^6 years), the period evolution is then given by

$$P^2(t) = P_0^2 + \frac{2}{(2-\alpha)}\frac{b}{a}B_0^{2-\alpha}\left[1 - (1 + a\alpha B_0^\alpha t)^{(\alpha-2)/\alpha}\right] \tag{4}$$

P_0 being the initial period. At old times this immediately gives an asymptotic period $P_\infty \propto B_0^{(2-\alpha)/2}$ of the order of 170, 40, and 8 s, for avenues A, B, and C respectively, assuming an initial field of 10^{15} G. In magnetars, the period P_∞ is reached while the field strength is still larger than $\sim 10^{13}$ G, where equation (2) applies.

3.2. *Evolution in the $P - \dot{P}$ Diagram*

Figure 2 illustrates tracks of the rotational evolution in the three field decay scenarios on $P - \dot{P}$ diagrams, comparing them with the observed values for the five AXPs.

Notice that the time t appearing in equation (4) is the 'real' age of the star (which we will call the model age $t_{\rm mod}$). While the field has not yet decayed and the period is much larger than the initial period, the model age coincides with the spin-down age $t_{\rm sd} \equiv P/2\dot{P}$ but later on $t_{\rm mod} < t_{\rm sd}$, a general feature of any field decay model.

In case A all observed AXPs would have a magnetic field still very close to its initial value and thus their ages are given by the spin-down age. In case B the field decay proceeds faster than in A and the observed AXPs would be approaching the stage of power-law field decay while in case C (the fastest decay scenario) their fields would already have undergone some decay. In the latter case the model ages are hence much lower than the spin-down ages, particularly for the lower field AXPs for which $t_{\rm mod} \sim 10^4$ yr while $t_{\rm sd} \sim 10^5$ yr.

A second striking difference between the avenues A and B against C concerns the location of the observed AXP periods relative to P_∞. While in A and B AXPs will still undergo a noticeable period increase, in C the whole class of objects would have already attained the saturation period. Finally, it is interesting to notice that within avenue C all AXPs seem to be born within a much narrower distribution of B_0 than in avenues A and B.

3.3. *Thermal X-Ray Luminosity*

We now discuss the X-ray detectability of thermal emission from our model sources. In cases A and B these X-ray luminosities have been calculated by H&K and we here use their results, while for case C we use the results of Geppert et al. (1999).

A basic feature of the thermal evolution with decaying magnetic field is that longer decay time scales imply longer lifetimes for detectable thermal X-ray luminosities which are then powered exclusively by the field decay. Accordingly, avenue A may keep luminosities above 10^{31} erg s^{-1} (i.e., surface temperatures around $3 - 4 \cdot 10^5$ K) for a few million years, while avenues B and C for just about one million years. This luminosity would allow the model sources to be detected within a few hundred parsecs.

In contradistinction, during the early phases, $\sim 10^3 – 10^4$ yr, when the thermal luminosity is above 10^{34} erg s^{-1}, the differences between models A and B as compared to C are not so large. This is due to a delicate balance between heating from field decay and neutrino losses together with the initial heat content of the star and the transmission properties of the strongly magnetized envelope. We take the reference value of 10^{34} erg s^{-1} as a lower limit for the visibility of the thermal component of AXPs. In each model the position where this luminosity is attained is marked in Figure 2 by a grey bar on the evolutionary tracks. All models assumed an iron envelope. For light element enriched envelopes, the early thermal evolution would not be affected but the observable thermal luminosities would rise by almost one order of magnitude. The grey bars in Figure 2 would then correspond to about 10^{35} erg s^{-1}.

4. DISCUSSION

To address the question raised in the introduction, we now want to combine our above results on the rotational evolution and on the thermal evolution. We do not consider explicitly the SGRs in this work since their spin-down is certainly not as steady as for AXPs and the use of the simple magnetic dipolar radiation braking law may be strongly misleading (see, e.g., Harding, Contopoulos & Kazanas 1999). In contradistinction, 1E 1841-045 has shown an extremely regular spin-down over more than ten years (Gotthelf, Vasisht & Dotani 1999) and the "bumpy" spin-down observed in 1E1048.1-5937 and 1E 2259+586

can be interpreted within the magnetar hypothesis assuming a "radiative precession" superposed to the standard magnetic dipole radiation braking (Melatos 1999; see also Kaspi, Chakrabarty & Steinberger 1999).

The two sources 1E 2259+586 and 4U 0142+61 have model ages around 10^5 yr in both avenues A and B, and hence their predicted thermal X-ray luminosities would be much fainter than observed, as indicated by the location of the grey bars in Figure 2. On the other hand, in the case of avenue C these objects are much younger and thus bright enough to be compatible with the observations. One possibility to reconcile A and B with observations is to invoke the presence of H/He envelopes in these two stars to raise their predicted thermal luminosity. However, this may raise another problem when interpreting the evolutionary tracks for the higher field of 10^{15} G. If we also assume the presence of light element envelopes in these paths, this would imply a shift in the limiting age for X-ray detectability from around 10^4 yr up to at least 10^5 yr (i.e., a shift of the grey bar in Figure 2) due to the action of the decaying field. The first consequence of this shift would be a large enhancement of the detection probability of sources on these tracks while only three AXPs are located there, 1E 1048.1-5937, 1E 1841-045 and 1RXS J170849-40091, and all three are very young. Second, along these tracks the period would still be increasing toward the asymptotic value and would exceed the presently observed ones. This problem is particularly severe for avenue A. However, within avenue C the five AXPs are well within the predicted X-ray detectability range and there is no need to invoke the presence of a light element envelope. Moreover, even if light elements were present they would not significantly raise the limiting age for detectability because of the much faster cooling in avenue C, a result of the much faster field decay.

As a last remark we want to notice that scenario C hints for AXPs being a class of neutron stars born with initial magnetic field within a very narrow strip around 10^{15} G. As a consequence, the young AXPs 1E 1841-045, 1E 1048-5947 and 1RXS J170849-40091, with model age of 10^3 yr, appear as the precursors of the older ones 4U 0142+61 and 1E 2259+586, with model age of 10^4 yr. In contrast, for a not so fast decayed field, as in cases A and B, it is difficult to explain the absence of the younger, and consequently X-ray brighter, precurring sources of 4U 0142+61 and 1E 2259+586, the last two with model age 10^5 yr.

5. CONCLUSIONS

In this letter we show that within the fastest field decay illustrated by avenue C, all five AXPs are located on tracks which have already reached their asymptotic period ~ 8 seconds. This constitutes a natural explanation of the observed period clustering of the five AXPs with measured period derivatives as well as of the AXP candidate AX J1845-0258. On the contrary, within the slower field decay scenarios A and B, this clustering of periods appears more contrived. We will now mention several consequences of this proposed scenario C that may in future be tested.

RXJ 0720.4-3125, a recently discovered nearby isolated neutron star (Haberl et al. 1997) with a rotation period of 8.39 s and purely thermal X-ray luminosity of 10^{31} erg s^{-1} is a candidate for a middle aged magnetar (Heyl & Hernquist 1998; H&K). Heyl & Hernquist considered constant magnetic field models while H&K used their results within avenues A and B, and interpreted the observed X-ray luminosity as powered by the dissipation of the magnetic energy. Within the interpretations of these authors, this source should have a field at birth slightly lower than the one of the AXPs to explain that its period is only 8.39 s despite of its age, and a period derivative (not yet determined) of a few times 10^{-13} s s^{-1}. Avenue C nicely predicts the existence of a population of objects similar to RXJ 0720.4-3125, with periods around 8 s or slightly longer, but with smaller derivative. At ages about 10^5 - 10^6 yr they have a luminosity of the order of $10^{31} - 10^{32}$ erg s^{-1} and period derivatives between 10^{-14} and 10^{-16} s s^{-1}. The measurement of $\dot{P}$ for RXJ 0720.4-3125 will enable us to discriminate among the different avenues. Notice that if the source is rather powered by accretion from the interstellar medium (Wang 1998; Konenkov & Popov 1997) then its period derivative should be below 10^{-16} s s^{-1}.

The two AXPs 1E 1841-045 and 1E 2259+586 are associated with the SNRs Kes 73 and CTB 109 respectively (Gotthelf & Vasisht 1997; Parmar et al. 1998). The sources spin-down ages and the ages of the SNRs are in discrepancy by factors of ~ 2.3 and 10, respectively. The field decay in avenue C is able to cure this problem naturally, but not A and B, as is clear from Figure 2.

A related interesting result of avenue C concerns the recently discovered radio pulsar PSR J1814-1744 (Camilo et al. 1999). With a 4 s period and a measured $\dot{P}$ of $7.4 \cdot 10^{-13}$ s s^{-1}, this radio pulsar is located, surprisingly, very close to the prototype AXP 1E 2259+586. If we try to include it as a radio-loud AXP (Pivovaroff et al. 1999), avenue C would predict an initial field somewhat below 10^{15} G and a model age of $\sim 10^4$ yr. This opens the possibility to detect the associated SNR. Within avenues A and B its age would be close to its spin-down age, i.e., 85000 years.

Our conclusion is thus that the dipolar component of the magnetic field of highly magnetized neutron stars must have a very short decay time scale. The crustal magnetic field hypothesis on which avenue C is based gives the indication that the decay time scale, in magnetars, is actually controlled by physical processes occurring in the crust. Assuming that strong magnetic fields permeate the stellar core, we can only conjecture that this may imply the action of some efficient mechanism of flux expulsion from the core into the crust, possibly in the line described, for example, by Srinivasan et al (1990).

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REFERENCES

Camilo, F., et al. 1999, Nature, submitted
Coe, M.J., & Pightling, S.L. 1998, MNRAS, 299, 223
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Gaensler, B.M., Gotthelf, E.V., & Vasisht, G. 1999, ApJ, 526, L37
Geppert, U., Page, D., Colpi, M., & Zannias, T. 1999, to appear in the proceedings of the IAU Colloquium 177 (e-print: astro-ph/9910563)
Gotthelf, E.V., & Vasisht, G. 1997, ApJ, 486, L133
Gotthelf, E.V., & Vasisht, G. 1998, New Astronomy, 3, 293
Gotthelf, E.V., Vasisht, G., & Dotani, T. 1999, ApJ, 522, L49
Goldreich, P., & Reisenegger, A. 1992, ApJ, 395, 250
Haberl, F., et al. 1997, A&A 326, 662
Harding, A. K., Contopoulos, I., & Kazanas, D. 1999, ApJ, 525, L125
Heyl, J. S. & Hernquist, L. 1998, MNRAS, 297, L69
Heyl, J. S., & Hernquist, L. 1998, MNRAS, 300, 599
Heyl, J. S., & Kulkarni, S. R. 1998, ApJ, 506, L61
Israel, G.L., Mereghetti, S., & Stella, L. 1994, ApJ, 433, L25
Israel, G.L., et al. 1999, ApJ, 518, L107
Kaspi, V.M., Chakrabarty, D., & Steinberger, J. 1999, ApJ, 525, L33
Konenkov, D. Yu., & Popov, S.B. 1997, AstL, 23, 498
Melatos, A. 1999, ApJ, 519, L77
Mereghetti, S., & Stella, L. 1995, ApJ, 442, L17
Mereghetti, S., Israel, G. L., & Stella, L. 1998, MNRAS, 296, 689
Oosterbroek, T., et al. 1998, A&A, 334, 925
Page, D. 1998, in Neutron Stars and Pulsars, eds N. Shibazaki, N. Kawai, S. Shibata, & T. Kifune, (Universal Academy Press: Tokyo), p. 183.
Parmar, A. N., et al. 1998, A&A, 330, 175
Pivovaroff, M., Kaspi, V. & Camilo F. 1999, to appear in the proceedings of the IAU Colloquium 177
Srinivasan, G., Bhattacharya, D., Muslimov, A. G., & Tsygan, A. I. 1990, Curr. Sci., 59, 31
Sugizaki, M., et al. 1997, PASJ, 49, L25
Taylor, J. H., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529
Thompson, C., & Duncan, R. C. 1996, ApJ, 473, 322
Torii, K., et al. 1998, ApJ, 503, 843
Vasisht, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
Wang, J.C.L. 1998, ApJL, 497, L55
Woltjer, L. 1964, ApJ, 140, 1309

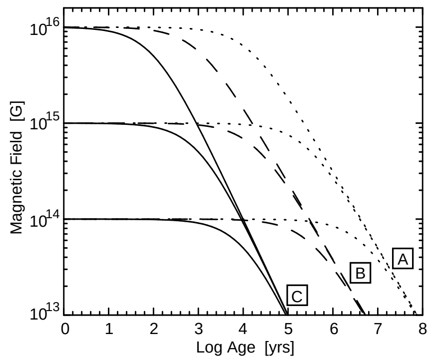

FIG. 1.— Magnetic field evolution in avenues A (ambipolar diffusion in the irrotational mode: $a = 0.01$ and $\alpha = 5/4$), B (ambipolar diffusion in the solenoidal mode: $a = 0.15$ and $\alpha = 5/4$), and C (crustal Hall cascade: $a = 10$ and $\alpha = 1$), for various initial field strengths following equation (3).

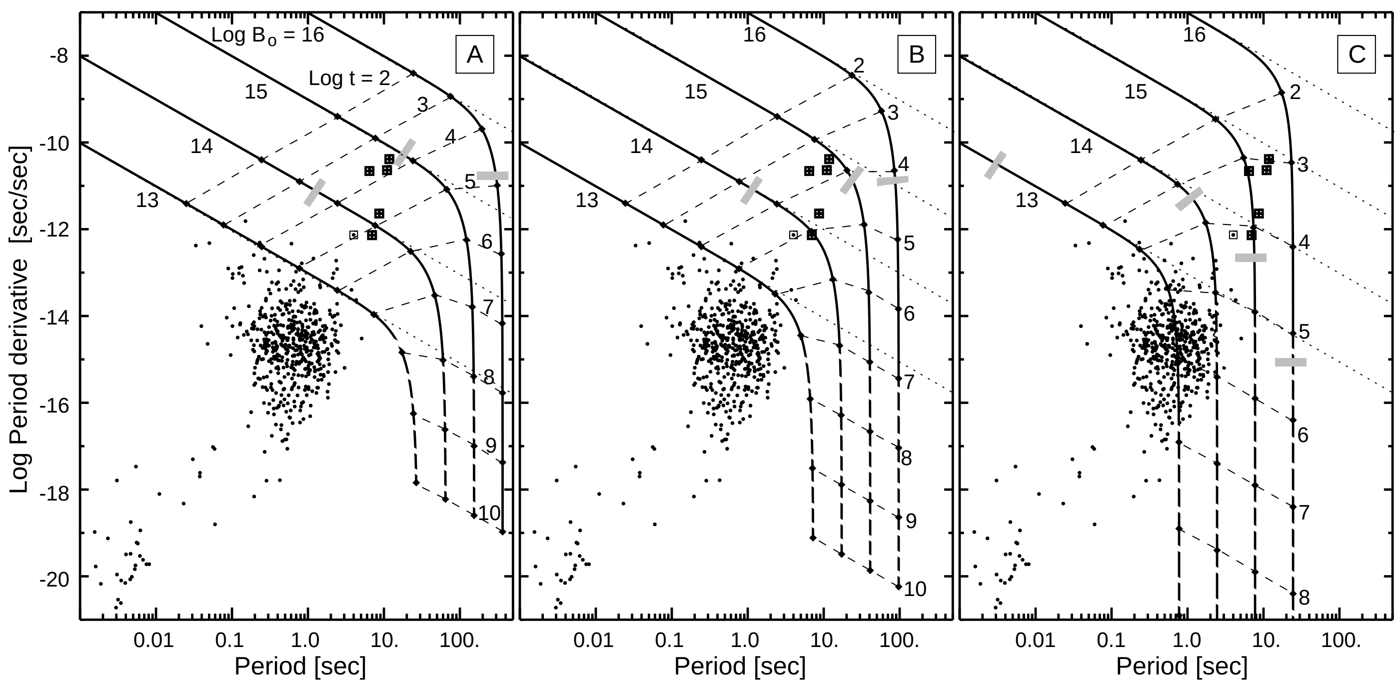

FIG. 2.— Evolutionary tracks (solid lines) for avenues A, B, and C in the $P - \dot{P}$ diagram. The initial magnetic field strength B_0 is indicated for each curve and the light dotted lines show evolution for a constant magnetic field. On each track diamonds give the logarithm of the model age in years, as labeled, and are connected by dashed lines for easier reading. The grey bars indicate when our model thermal X-ray luminosity, estimated for neutron stars with iron envelopes, drops below 10^{34} erg s^{-1}. The evolutionary paths may not be reliable when the field drops below 10^{13} G since our decay law (Eq.[2]) could be inapplicable below the magnetar regime: they are marked as broken in this region since they could actually move to higher periods. Radio pulsars from the Princeton catalogue (Taylor, Manchester, & Lyne 1993) are plotted as dots and the boxed pulsar is PSRJ1814-1744 (Camilo et al. 1999). The five AXPs, shown as boxed crosses, in order of decreasing period derivatives are 1E 1841-045 (Vasisht & Gotthelf 1997), 1RXS J170849-40091 (Sugizaki et al. 1997; Israel et al. 1999), 1E 1048-5947 (Oosterbroek et al. 1998), 4U 0142+61 (Israel et al. 1994), and finally 1E 2259+586 (Parmar et al. 1998).